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J.W. Castellani, C.O'Brien, P. Tikuisis, I.V. Sils, X. Xu

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Thermal and Mountain Medicine Division
U.S. Army Research Institute of Environmental Medicine
Natick, MA 01760-5007

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13. ABSTRACT *(Maximum 200 words)*
Cold thermoregulatory models (CTM) have primarily been developed to predict core temperature (Tcore) responses during sedentary immersion. Few studies have examined their efficacy to predict Tcore during exercise-cold exposure. The purpose of this study was to compare observed Tcore responses during exercise in cold water with the predicted Tcore from a 3-cylinder (3-CTM) and a 6-cylinder (6-CTM) model, adjusted to include heat production from exercise. A matrix of two metabolic rates (0.44 and 0.88 m/s walking), two water temperatures (10 and 15 degrees C), and two immersion depths (chest and waist) were used to elicit different rates of Tcore changes. Root mean square deviation (RMSD) and non-parametric Bland-Altman tests were used to test for acceptable model predictions. Using the RMSD criterion, the 3-CTM did not fit the observed data in any trial, whereas the 6-CTM fit the data (RMSD less than standard deviation) in 4/8 trials. In general, the 3-CTM predicted a rapid decline in core temperature followed by a plateau. For the 6-CTM, the predicted Tcore appeared relatively tight during the early part of immersion but was much lower during the latter portions of immersion, accounting for the non-agreement between RMSD and SD values. The 6-CTM was re-run with no adjustment for exercise metabolism and core temperature and heat loss predictions were tighter. In summary, this study demonstrated that both thermoregulatory models designed for sedentary cold exposure, currently, can not be extended for use during partial immersion exercise in cold water. Algorithms need to be developed to better predict heat loss during exercise in cold-water.

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Evaluation of two cold thermoregulatory models for prediction of core temperature during exercise in cold water

John W. Castellani,[1] Catherine O'Brien,[1] Peter Tikuisis,[3] Ingrid V. Sils,[1] and Xiaojiang Xu[2]

[1]*Thermal and Mountain Medicine Division and* [2]*Biophysics and Biomodeling Division, US Army Research Institute of Environmental Medicine, Natick, Massachusetts; and* [3]*Defence Research and Development Canada-Toronto, North York, Ontario, Canada*

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Castellani JW, O'Brien C, Tikuisis P, Sils IV, Xu X. Evaluation of two cold thermoregulatory models for prediction of core temperature during exercise in cold water. *J Appl Physiol* 103: 2034–2041, 2007. First published September 20, 2007; doi:10.1152/japplphysiol.00499.2007.—Cold thermoregulatory models (CTM) have primarily been developed to predict core temperature (T_{core}) responses during sedentary immersion. Few studies have examined their efficacy to predict T_{core} during exercise cold exposure. The purpose of this study was to compare observed T_{core} responses during exercise in cold water with the predicted T_{core} from a three-cylinder (3-CTM) and a six-cylinder (6-CTM) model, adjusted to include heat production from exercise. A matrix of two metabolic rates (0.44 and 0.88 m/s walking), two water temperatures (10 and 15°C), and two immersion depths (chest and waist) were used to elicit different rates of T_{core} changes. Root mean square deviation (RMSD) and nonparametric Bland-Altman tests were used to test for acceptable model predictions. Using the RMSD criterion, the 3-CTM did not fit the observed data in any trial, whereas the 6-CTM fit the data (RMSD less than standard deviation) in four of eight trials. In general, the 3-CTM predicted a rapid decline in core temperature followed by a plateau. For the 6-CTM, the predicted T_{core} appeared relatively tight during the early part of immersion, but was much lower during the latter portions of immersion, accounting for the nonagreement between RMSD and SD values. The 6-CTM was rerun with no adjustment for exercise metabolism, and core temperature and heat loss predictions were tighter. In summary, this study demonstrated that both thermoregulatory models designed for sedentary cold exposure, currently, cannot be extended for use during partial immersion exercise in cold water. Algorithms need to be developed to better predict heat loss during exercise in cold water.

heat content; hypothermia; shivering

LEG EXERCISE CAN DEFEND AGAINST a drop in core temperature (T_{core}) during immersion at water temperatures >18°C, but, at lower water temperatures, heat loss is often greater than heat production, resulting in a fall in T_{core} (13, 14). Predicting the T_{core} response during exercise in immersed conditions using thermoregulatory models would enable the development of exposure guidelines for active persons to reduce the risk of hypothermia. However, existing cold thermoregulatory models (CTMs) were originally developed for sedentary immersion (20, 21, 24, 25, 31, 33) and have not taken exercise into consideration. It is not known whether these models can be used to accurately predict T_{core} responses during combined exercise and immersion.

Two models often employed for sedentary cold water immersion are a three-cylinder CTM (3-CTM) developed by Tikuisis (20, 21) and a six-cylinder CTM (6-CTM) developed by Xu and Werner (33). The 3-CTM is an extension of a two-cylinder torso model, where one cylinder was exposed to air and the other exposed to water (20, 21). The model was extended by adding a third cylinder that represented the legs. The 6-CTM describes the human body using six cylinders (head, trunk, arms, legs, hands, and feet) with heat loss adjustments based on whether a particular cylinder is exposed to air, water, or both. The 6-CTM also assumes a redistribution of blood to the thorax and a transient rise in T_{core}, whereas the 3-CTM does not model these initial physiological responses to cold. Each model predicts shivering heat production from T_{core} and skin temperature and percent body fat, but they do so with different mathematical relationships (22, 23). To predict T_{core} responses during exercise, both models need to be adjusted to account for the additional metabolic heat production ($\dot{M}$) caused by exercise. Thus exercise metabolic rate was added to each model by using the prediction equation of Pandolf et al. (16). This equation uses subject mass, load carried/clothing weight, walking speed, grade, and a terrain factor for walking in water to estimate energy expenditure during exercise. In the case of the 3-CTM model, this modification was done to provide guidance for US Army units exercising in cold water following several fatalities (34).

The purpose of this study was to evaluate the 3-CTM and 6-CTM and determine their efficacy during exercise and cold exposure. We compared T_{core} responses during exercise in cold water with the predicted T_{core} from the 3-CTM and 6-CTM models, adjusted to include heat production from exercise. A matrix of two metabolic rates (0.44 and 0.88 m/s walking), two water temperatures (10 and 15°C), and two immersion depths (chest and waist) were used and were intended to elicit different rates of T_{core} changes over time. The experimental conditions were chosen to simulate partial immersions that may be encountered during stream crossings during military operations and search-and-rescue missions (34). It was hypothesized that both models would provide a valid prediction of the change in T_{core} during leg exercise, but that the 6-CTM would more closely model the T_{core} change as it accounts for the initial transient rise in T_{core} and, by estimating heat exchange with more cylinders, can simulate the complexity of the T_{core} response to partial immersion and lower body exercise.

Address for reprint requests and other correspondence: J. W. Castellani, Thermal and Mountain Medicine Division, US Army Research Institute of Environmental Medicine, 42 Kansas St., Natick, MA 01760-5007 (e-mail: john.castellani@us.army.mil).

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METHODS

Subjects. Ten male volunteers provided written, informed consent to participate in this study, which was approved by the Scientific and Human Use Review Boards of the US Army Research Institute of Environmental Medicine and the US Army Medical Research and Materiel Command. The subjects volunteered after being fully informed of the requirements and risks associated with the research. Subject characteristics [mean (SD) and range] were as follows: age, 20 yr (SD 2), 18–25 yr; height, 178 cm (SD 7), 170–193 cm; body mass, 73.4 kg (SD 7.1), 65.4–86.6 kg; body surface area, 1.89 m^2 (SD 0.10), 1.75–2.04 m^2; peak O_2 uptake ($\dot{V}O_2$), 47.2 $ml \cdot kg^{-1} \cdot min^{-1}$ (SD 4.8), 38.9–57.1 $ml \cdot kg^{-1} \cdot min^{-1}$; percent body fat, 15.5% (SD 3.9), 5.5–19.2%; and subcutaneous fat thickness 3.1 mm (SD 1.4), 0.18–5.0 mm.

Preliminary testing. Body composition was measured using dual-energy X-ray absorptiometry (model DPX-L, Lunar, Madison, WI). Skinfolds were obtained from 10 sites (1), and subcutaneous fat thickness was calculated. Body surface area was computed from height and weight using the equation of DuBois and DuBois (5). An incremental cycle ergometer test was used for determination of peak $\dot{V}O_2$.

Familiarization. Before the experimental trials, all volunteers practiced, one time, walking on the underwater treadmill at 0.88 m/s (2 mph) for 10–15 min, at a water temperature between 12 and 13°C (~55°F) to become familiar with the laboratory equipment and the stress of cold water exposure. Subjects dressed in Army battle-dress uniforms and neoprene water shoes for all trials. Subjects were fully instrumented for this familiarization session.

Subjects also performed three more familiarization sessions to "train" the muscles involved in walking on an underwater treadmill. This consisted of 0.88 m/s walking in waist-deep water for 90 min at a water temperature of 27°C.

Experimental design. Subjects walked at two speeds (0.44 $m \cdot s^{-1} \cdot 1.0\ mph^{-1}$ and 0.88 $m \cdot s^{-1} \cdot 2.0\ mph^{-1}$), at two different immersion depths [chest (C) and waist (W)], and at two different water temperatures (10 and 15°C). Each combination was tested once for each subject (8 trials) and randomized. Trials are denoted by water temperature followed by immersion depth and finally by walking speed. Thus immersion in 10°C at the chest and walking at 1 mph is denoted as 10C1 (other trials are 10C2, 10W1, 10W2, 15C1, 15C2, 15W1, and 15W2). Subjects during chest experiments were immersed to the nipple, and during waist experiments were immersed to the iliac crest. On another day, five subjects walked fully instrumented for 1 h in 30°C water (chest level) at 0.88 m/s to assess the metabolic costs of exercise in the water without cold exposure. All trials were separated by at least 1 day.

Following a light breakfast of ~500 kcal (e.g., bagel, juice, and a piece of fruit) and instrumentation, subjects completed a cognitive test battery for ~35 min, at which time baseline temperatures were measured. They then completed a preexercise, resting $\dot{V}O_2$ measurement for 5 min. Following this, they walked into the immersion pool, were positioned on the underwater treadmill (Aqua-Gaiter, Ferno, Wilmington, OH), and began walking at the appropriate speed, depth, and water temperature for the test day. Subjects walked until one of the following occurred: their rectal temperature (T_{re}) reached 35.5°C, they had exercised for 4 h, the subject asked to stop, or subject's exposure was stopped by the principal investigator. At ~2 h of exercise, subjects were given ~250 ml of fruit juice to maintain plasma glucose levels. Each subject's trial began at approximately the same time each day. No caffeine or alcohol was consumed on the test day. If subjects smoked, they could do so before beginning an experimental day, but were not able to have any other nicotine for the remainder of the test session.

Measurements. T_{re} was measured using a rectal thermistor (YSI, Yellow Springs, OH) inserted 10 cm beyond the anal sphincter. Skin temperature (°C) and heat flow (HF; W/m^2) were measured by HF sensors with an integrated thermistor (Concept Engineering, Old Saybrook, CT) attached to the skin surface at eight sites (on the right side): anterior aspect of forearm, forehead, subscapular, triceps, pectoralis major, abdomen (7.5 cm lateral to umbilicus), anterior thigh, and calf. Temperature data were collected every 15 s during treadmill walking (PX 1006, National Instruments). $\dot{V}O_2$ was determined using an online metabolic analysis system (V_{max}, Sensormedics, Yorba Linda, CA) before exercise and every 20 min during walking. Subject's expired air was collected for 5 min each time using a mouthpiece and nose clip. Heart rate was measured from three electrodes (CM-5 configuration) hardwired to an oscilloscope-cardiotachometer (Hewlett-Packard, Andover, MA).

Calculations. Mean weighted HF was calculated using eight sites (19). A seven-site formula with the following weighting factors (0.06 $HF_{forearm}$, 0.185 $HF_{subscapular}$, 0.09 $HF_{triceps}$, 0.095 $HF_{pectoral}$, 0.18 $HF_{abdomen}$, 0.2 HF_{thigh}, and 0.19 HF_{calf}) was first computed and then multiplied by 0.93. This number was then added to $0.07 \cdot HF_{forehead}$ for determination of mean HF (19). $\dot{M}$ (W/m^2) was estimated from the $\dot{V}O_2$ and respiratory exchange ratio (RER) using the following equation (7): $\dot{M} = [0.23(RER) + 0.77] \cdot (5.873 \cdot \dot{V}O_2) \cdot (60/A_D)$, where A_D (5) is body surface area (m^2). Body heat storage (S) was calculated using partitional calorimetry (7, 29), i.e., $\pm S = \dot{M} - L - (R + C)$, where L ($0.08 \cdot \dot{M}$) is the respiratory heat losses by convection and evaporation, and R + C represents radiative and convective heat loss and is determined from weighted (same weights as skin) HF (29). Work rate, evaporative heat loss, and conductive heat loss were assumed to be zero in this experiment. Heat debt is the cumulative heat loss integrated over time. Since $\dot{M}$ was measured every 20 min, it was assumed that the $\dot{M}$ for the preceding 20-min time period was equal to this measured value. Insulation values (clo) for clothing over the thigh (all trials) and abdomen (chest trials only) were calculated at *minute 40* of exposure using the formula:

$$clo = [T_{thigh\,(abdomen)} - T_{water}] \cdot [HF_{thigh\,(abdomen)} \cdot 0.155]^{-1} \quad (1)$$

where T is temperature. This value was then reduced by 0.02 clo to account for boundary layer insulation as measured on a copper manikin (Joe Giblo, US Navy, personal communication).

Thermoregulatory models. The 3-CTM model details can be found in two previous studies (20, 21). To simulate partial immersion, the original model consists of two cylinders aligned end to end to simulate the torso. The convention is to air expose the upper cylinder and water immerse the lower cylinder, with each cylinder usually having a different change in mean temperature. The algorithm to calculate the resultant change in deep T_{core} (taking into account the geometric correspondence between the body and model cylinder, and avenues of heat loss other than conduction) is outlined in Ref. 20. The 3-CTM added a leg cylinder to the torso model and can be air exposed or water immersed. The 3-CTM was developed in response to incidents of hypothermia of exertionally fatigued individuals walking in cold water (34).

Inputs to the 3-CTM include individual characteristics (height, weight, %fat, age, fatigue factor), environmental characteristics (air and water temperature, immersion depth, wind speed, water speed, solar radiation, relative humidity), clothing characteristics (insulation, wetness), and exercise characteristics (walking speed, %grade, terrain coefficient, weight of clothing and equipment). Input for the fatigue factor was set at 100, which assumed that all subjects were at their maximal performance capability. Water speed was set at the walking speed. Wind speed and solar radiation were set at 0. $\dot{M}$ from exercise was predicted from the equation of Pandolf et al. (16). Shivering $\dot{M}$ was predicted from Tikuisis et al. (23) and is embedded within the model.

The 6-CTM model was derived from two previous thermoregulatory models (18, 30). The 6-CTM describes the human body as a passive system of six cylinders: head, trunk, arms, legs, hands, and feet. Each cylinder is further concentrically divided into compartments representing the core, muscle, fat, and skin. Blood is represented as a one-loop circulatory system and is an independent compartment. Thus the human body is represented by 25 compartments. The sizes of the compartments are determined from height, weight, and body fat percentage (32, 33).

Of the six cylinders, the head, arms, and hands were always exposed to the air, and the legs and feet were always immersed. The trunk cylinder was exposed to both air and water of varying depth, and the clothing insulation covering the trunk was in transition. Thus the environmental and clothing parameters for the trunk were modified to take these factors into account. Based on the experimental design, it was assumed that, during chest immersion, 20% of the torso was exposed to air while 80% was immersed, whereas, during waist immersion, 80% of the torso was exposed to air while 20% was immersed.

6-CTM inputs include individual characteristics (i.e., height, weight, fat percentage, age, maximum $\dot{V}O_2$), predicted external workload (16) for walking at 0.44 and 0.88 m/s using a terrain coefficient of 1.8, and environmental (i.e., temperature, humidity, and wind velocity) and clothing (clothing insulation clo, moisture permeability index) parameters for each of the six cylinders. Shivering heat production was predicted from a published equation (22) and was embedded within the model.

The models used in this analysis use a standard initial starting T_{core}, the 3-CTM using 37°C and the 6-CTM using 36.8°C. We adjusted the model predictions by using changes in T_{core} rather than absolute temperatures so that we could compare between models.

Statistical analysis. Differences between observed changes in T_{re} and model predictions were evaluated by comparing the root mean square deviation (RMSD) of each trial with the observed standard deviation (10). This statistic is used to quantitatively determine the goodness of fit between model predictions and observed data. The RMSD (°C) is defined as

$$\mathrm{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2} \qquad (2)$$

where d_i is the difference between observed and predicted T_{core} response at each time point (°C), and n is the number of time points examined with an interval of 10 min used. The prediction was considered valid if the RMSD fell below the SD of the observed values (32).

Nonparametric Bland-Altman plots were also used to determine the level of agreement (2) between the observed and predicted delta T_{core} for the 3-CTM and 6-CTM using ±0.4°C as a qualitative physiological threshold for assessment. This threshold is twice the anticipated standard deviation for T_{core} (4), which accounts for unique and additive response variability likely to occur with experimental perturbations. Smaller differences are, therefore, within the acceptable noise of the measurement and were considered of marginal importance, independent of the P value. This procedure allows data evaluation against an evidentiary standard other than zero, similar to equivalence testing (6). Data were examined over time as well as at individual test endpoints.

$\dot{M}$, HF, and heat storage were analyzed using repeated-measures ANOVA (speed × depth) within a specific water temperature (10 and 15°C water temperatures were analyzed separately). When significant F-ratios were calculated ($P < 0.05$), paired comparisons were made post hoc using Tukey tests. Data are presented as means (SD). Level of significance was set as $P < 0.05$.

RESULTS

Study completion. Seven subjects completed all eight trials. Of the other three subjects, two completed 6 trials and one completed 5 trials, for a total of 73 trials completed by the subjects. The mean completion time (min) for each trial was as follows: 10C1 (n = 9): 76.8 (SD 40.8); 10C2 (n = 8): 95.1 (SD 38.1); 10W1 (n = 9): 85.6 (SD 40.7); 10W2 (n = 10): 92.7

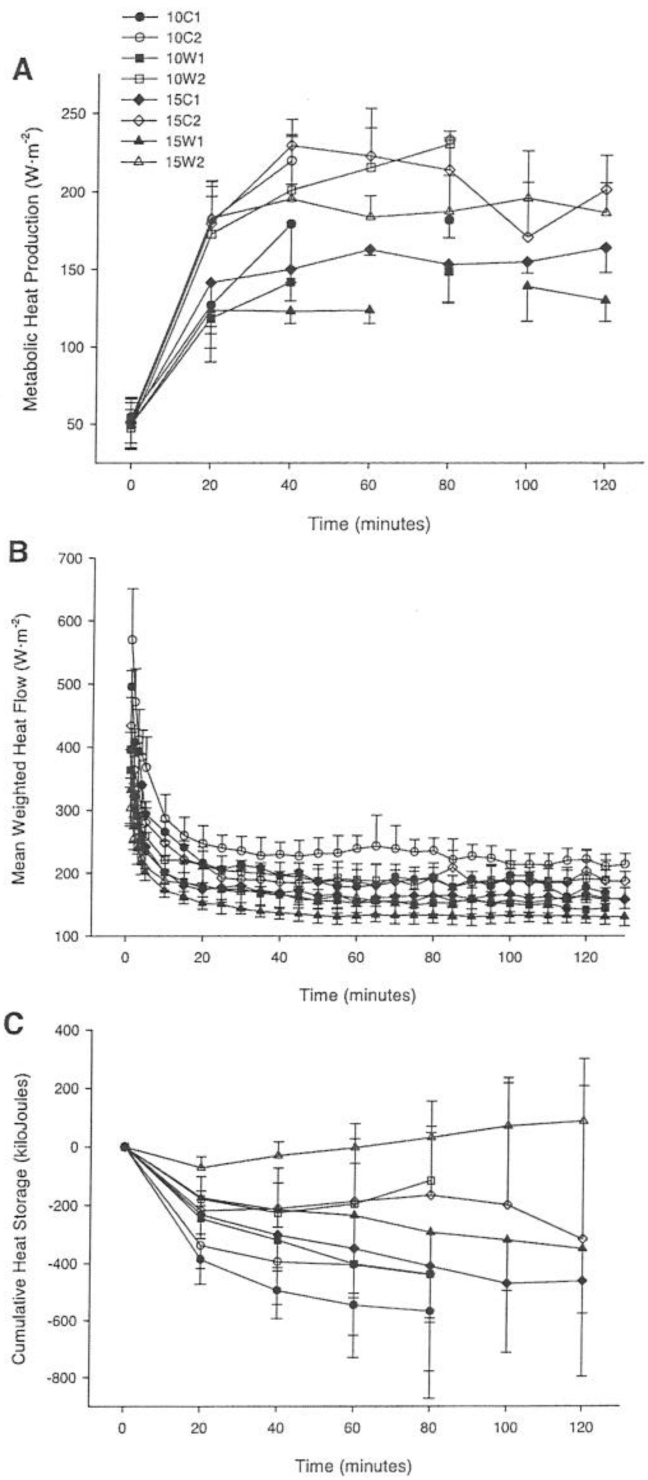

Fig. 1. Measured metabolic heat production (*A*), mean weighted heat flow (*B*), and heat storage (*C*) vs. time during cold water exercise in the 8 experimental trials, which are denoted by water temperature followed by immersion depth and finally by walking speed [10 and 15 represent water temperature in °C; C (chest) and W (waist) represent immersion depths; 1 and 2 represent speed in mph].

(SD 38.1); 15C1 ($n = 9$): 118.0 (SD 39.1); 15C2 ($n = 9$): 117.1 (SD 40.7); 15W1 ($n = 9$): 149.5 (SD 59.7); and 15W2 ($n = 10$): 163.1 (SD 48.3). Overall, subjects walked for a longer duration at 15 vs. 10°C ($P = 0.002$) and for a longer duration when immersed to the waist vs. chest ($P = 0.01$). Within the 10°C trials, subjects walked for a longer time ($P = 0.03$) at 0.88 vs. 0.44 m/s, but there was no difference for the immersion depth. In contrast, at 15°C, there was a depth effect, with subjects going longer ($P = 0.001$) at the waist vs. chest, but there was no difference between walking speeds. Reasons for stopping included reaching a T_{core} of 35.5°C, volitional exhaustion, being stopped by the investigator due to gait changes during walking, and in one trial, completing the 240-min bout.

Physiological responses. $\dot{M}$ increased during the first 20–40 min of immersion and then exhibited a plateau during the final 40–60 min of immersion (Fig. 1*A*). $\dot{M}$ was higher during exercise at 0.88 m/s, with no differences between immersion depths. HF was high upon initial exposure to cold water, but fell quickly as a result of vasoconstriction, with steady-state values reached by 30–40 min of exercise (Fig. 1*B*). Figure 1*C* presents the cumulative heat storage measured by partitional calorimetry. Overall, there was less of a decline in heat storage during exercise at 15°C ($P = 0.013$), 0.88 m/s ($P = 0.005$), and waist level immersion ($P = 0.003$), compared with 10°C, 0.44 m/s, and chest immersion, respectively.

Model comparisons. Figures 2 (10°C) and 3 (15°C) show the observed T_{re} (mean ± SD) of each trial across time along with the mean predicted T_{core} for each model.

The SD and RMSD for each trial are presented in Table 1. Using the RMSD criterion, the 3-CTM did not fit the observed data in any trial. In general, the 3-CTM predicted a rapid decline in T_{core} followed by a plateau. The 6-CTM fit the data (RMSD < SD) in four out of eight trials, with the RMSD value less than the observed SD in three of the 10°C trials and in one of the 15°C trials (15W1). For the 6-CTM, the predicted T_{core} appeared relatively tight during the early part of immersion, but was lower during the latter portions of immersion, accounting for the nonagreement between RMSD and SD values.

To better evaluate the practical importance of the differences between predicted and measured values, nonparametric Bland-Altman plots were constructed for each trial to determine what percentage of the predicted values fell within a 0.4°C qualitative threshold of importance. Figure 4 presents this data over time (from *minutes 10* to *120*) for all trials. Bland-Altman analysis confirmed the observation that the models were less predictive as exposure duration increased. The 3-CTM predicted 64% of the values early in exposure, and this decreased to 32%. The 6-CTM predicted 91% of the values in the first 30 min and subsequently decreased to 66% for the remainder of the 120-min exposure. Figure 5 presents the Bland-Altman plots for each individual test endpoint on every trial. For the 3-CTM, there were three trials (10C1, 10C2, 15C2) where >50% of the subject's predicted values were within 0.4°C of the observed values. For the 6-CTM, acceptable predictive thresholds were met for >50% of the subjects in seven trials

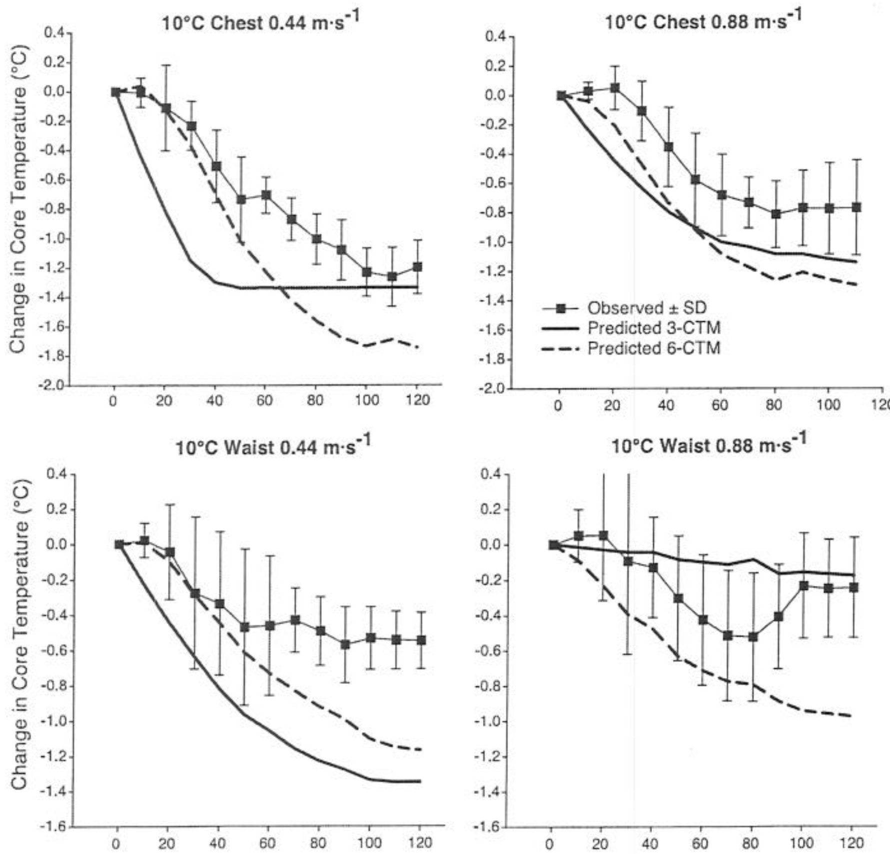

Fig. 2. Observed (mean ± SD) and predicted core temperatures vs. time during walking in the four trials conducted at 10°C water. 3-CTM and 6-CTM, three- and six-cylinder cold thermoregulatory model, respectively.

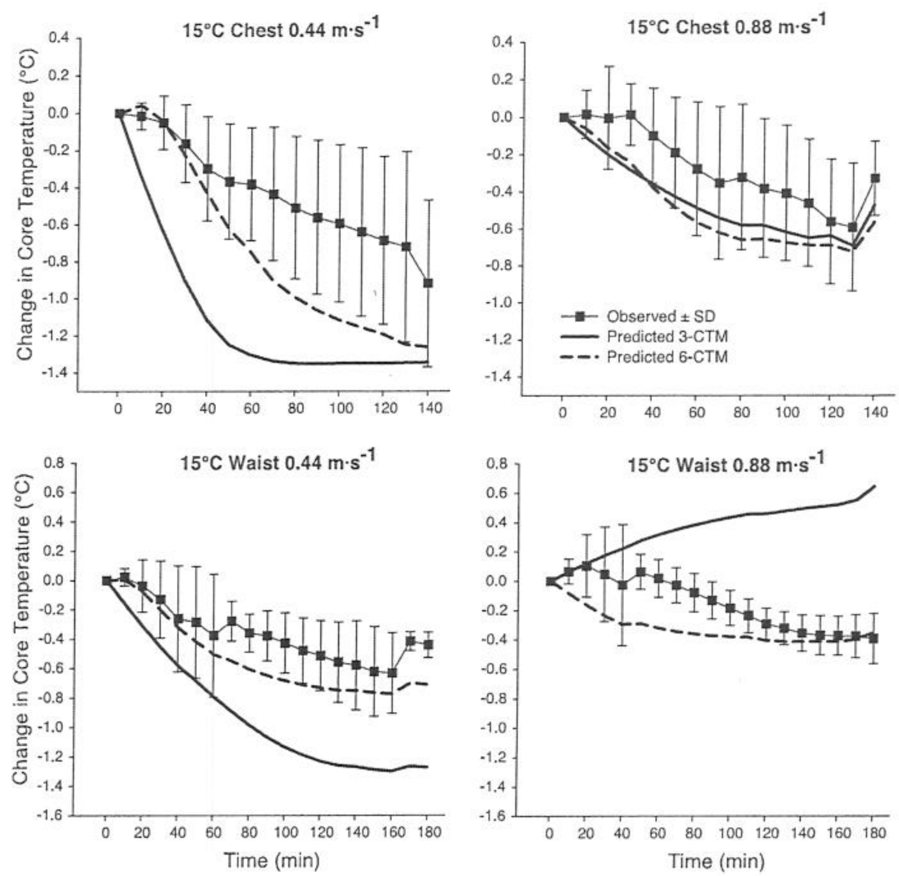

Fig. 3. Observed (mean ± SD) and predicted core temperatures vs. time during walking in the four trials conducted in 15°C water.

(10W1 only had 2 out of 9 subjects meet the 0.4°C threshold value).

Two prediction equations for shivering (22, 23) are used in the two thermal models, and these values were added to the predicted $\dot{M}$ for walking in water (16) to determine the predicted total $\dot{M}$ for each model. Predicted total $\dot{M}$ was compared with the $\dot{M}$ determined from indirect calorimetry. The average $\dot{M}$ (shivering + walking) for all trials using indirect calorimetry was 178.1 W/m^2 (SD 43.3). The 3-CTM, which used the Tikuisis et al. shivering equation added to the walking $\dot{M}$ (23) underpredicted $\dot{M}$ by ~15% [151.8 W/m^2 (SD 37.8), $P <$ 0.0001]; the 6-CTM, using the more recent shivering prediction from Tikuisis and Giesbrecht (22), overpredicted total $\dot{M}$ by ~21% [214.8 W/m^2 (SD 36.0), $P < 0.0001$]. To verify the accuracy of the Pandolf et al. (16) equation for exercising in water, $\dot{M}$ was determined in five subjects who walked at 0.88 m/s in 30°C water. There were no differences between ob-

Table 1. *Standard deviations and root mean square deviations for the three- and six-cylinder models during eight cold water trials*

Trial	No. of Subjects	Standard Deviation	RMSD for 3-CTM	RMSD for 6-CTM
10C1	9	0.441	0.592	0.303
10C2	8	0.395	0.404	0.369
10W1	9	0.360	0.489	0.346
10W2	10	0.317	0.414	0.339
15C1	9	0.264	0.711	0.334
15C2	9	0.260	0.286	0.285
15W1	9	0.299	0.529	0.250
15W2	10	0.218	0.614	0.252

Comparisons are for the change in rectal temperature. Trials are denoted by water temperature followed by immersion depth and finally by walking speed [10 and 15 represent water temperature in °C; C (chest) and W (waist) represent immersion depths; 1 and 2 represent speed in mph]. RMSD, root mean square deviation; 3-CTM and 6-CTM, three- and six-cylinder cold thermoregulatory model, respectively.

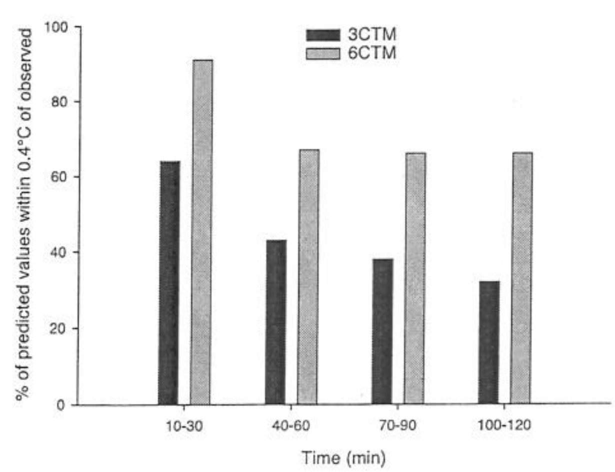

Fig. 4. Percentage of predicted values within ±0.4°C of the observed value determined using nonparametric Bland-Altman analysis. Data were collapsed for all eight trials and binned into four equal 20-min time intervals.

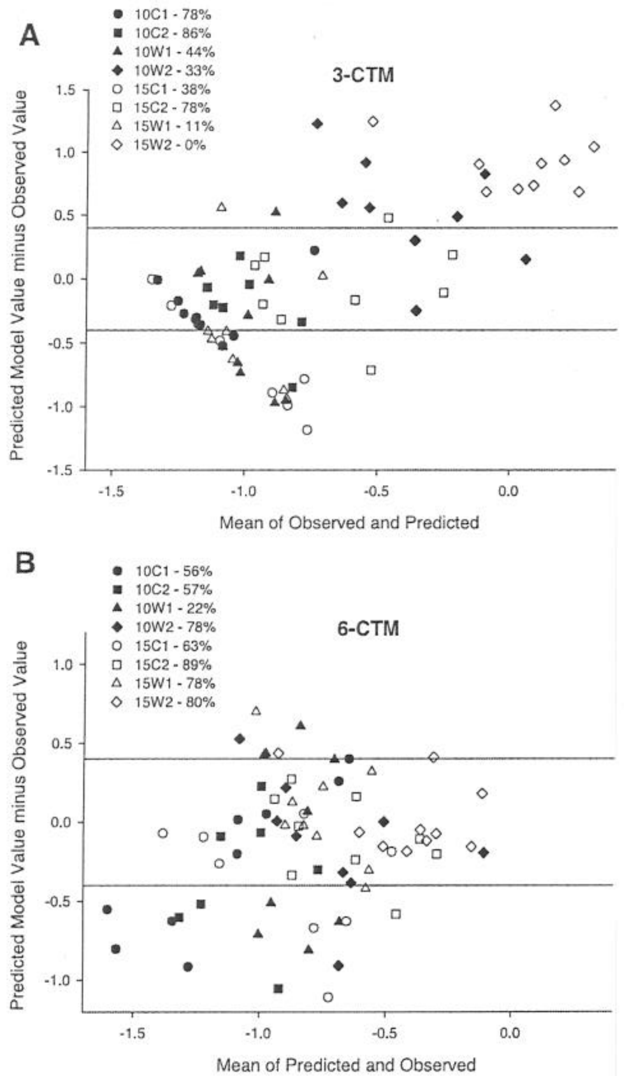

Fig. 5. Bland-Altman plots for the end-point temperature prediction in all trials using the 3-CTM (*A*) and 6-CTM (*B*) thermoregulatory models. Percentages shown are the percentage of subjects whose predicted values were within ±0.4°C of the actual measured value. Line shown is a qualitative threshold (±0.4°C) for prediction agreement.

served [142.8 W/m^2 (SD 25.3)] and predicted [146.2 W/m^2 (SD 8.8)] values for walking $\dot{M}$ in warm water; thus differences between observed and predicted total $\dot{M}$ appear to be due to the prediction of shivering heat production.

Clothing insulation values for the thigh ranged from 0.02 (SD 0.01) to 0.04 clo (SD 0.02) across all eight trials. During the chest immersions, the abdomen insulation value ranged from 0.01 (SD 0.00) to 0.03 clo (SD 0.01).

DISCUSSION

This study was the first to evaluate the ability of two CTMs (3-cylinder and 6-cylinder) to predict T_{core} responses during exercise and immersion. The 3-CTM model was evaluated because it was used to develop current cold-water guidance for the United States Army. Primary new findings from this study are as follows: *1*) the 3-CTM did not successfully predict T_{core}, using RMSD criterion, in any of the trials; *2*) the 6-CTM predicted T_{core} in four out of eight trials (10C1, 10C2, 10W1, 15W1) using RMSD criterion; and *3*) using Bland-Altman analysis, the 3-CTM and 6-CTM predicted >50% of the subjects' endpoint temperatures for three of eight and seven of eight trials, respectively, with ±0.4°C as the acceptable temperature threshold.

The better agreement in the six-cylinder thermoregulatory model, using the quantitative RMSD criterion, was primarily due to the close agreement between predicted and observed values during the initial responses (*minutes 10–50*) to cold-water exercise. Qualitative analysis of the data using Bland-Altman plots clearly indicate that the 6-CTM predicted within 0.4°C of observed values very well in the first 30 min of exposure (91%) and was still above 60% after 1 h. In contrast, the 3-CTM had a much lower percentage of predicted values within 0.4°C in the 1st h of exposure. It is during this period that T_{core} transiently increased before declining. In the 6-CTM, blood flow changes as a function of skin and T_{core}, with the assumption that blood will be shifted centrally to the thorax upon cold exposure, which will limit the initial decline in T_{core} and enable prediction of the transient rise. The 6-CTM is based on a model by Stolwijk and Hardy (18) that incorporated a rapid vasoconstriction upon cold exposure, which subsequently lowered peripheral blood flow and convective heat loss, reduced heat conduction from the core to the extremity, and caused an initial transient increase in T_{core}. In contrast, the 3-CTM purposely circumvents the initial transient changes to the cold and proceeds directly to a steady-state solution of body heat loss for computational ease and functionality. This conservative approach for predicting survival time in the 3-CTM, unfortunately, precludes its use for guidance development at higher end-point T_{core} (35.5°C).

As the exposure duration increased beyond 60 min, quantitatively, the predicted values were lower than observed in almost every trial (except in 15W2, where the 3-CTM significantly overpredicted the T_{core}). Qualitatively, the percentage of predicted values that were within 0.4°C of observed values decreased. This was the case in six trials for the 6-CTM and five trials for the 3-CTM. These models are based on the heat balance equation, so any deviation from observed values must be due to an under- or overprediction of $\dot{M}$ and/or peripheral heat loss. For total $\dot{M}$, errors could be in the prediction of exercise $\dot{M}$ or shivering $\dot{M}$. Our data from warm-water exercise suggest that the observed exercise $\dot{M}$ values were predicted well by the Pandolf et al. (16) equation, and our oxygen consumption values during the 30°C walks at 0.88 m/s in chest-high water (10.8 ml·kg^{-1}·min^{-1}) agree closely with the values of Gleim and Nicholas (11.2 ml·kg^{-1}·min^{-1}) at waist depth (8). However, the prediction of total $\dot{M}$ was different from observed values for both models, suggesting that the prediction of shivering was off. In the case of the 3-CTM model, the shivering prediction equation developed by Tikuisis et al. (23) underestimated $\dot{M}$ by 15% and could be a potential reason why predicted T_{core} are generally lower than observed. The 6-CTM, using another equation developed by Tikuisis and Giesbrecht (22), overpredicted $\dot{M}$ by 21%. This can be explained by the lack of shivering suppression due to exercise (12, 26), which was not accounted for in the development of the shivering response model (22) used in 6-CTM. Nevertheless, the overprediction of $\dot{M}$ by 6-CTM suggests that high-predicted heat loss, rather than $\dot{M}$, is the primary reason for the low-predicted T_{core} after 1 h. Table 2 presents the measured whole body HF values at *minute 60* and the model-derived values for the 6-CTM model. It is apparent that the model overpredicted heat loss, which would lead to a lower predicted T_{core}. To test the idea that the addition of exercise to the 6-CTM caused the overprediction of HF, we reran the 6-CTM for the 0.44 m/s trials but did not input the contribution from exercise (assumed a sedentary exposure).

The 6-CTM predicted the T_{core} decline better after 1 h of exercise when no external walking $\dot{M}$ was input for the 0.44 m/s trials (Fig. 6). Using the qualitative Bland-Altman analysis, the percentage of predicted values within 0.4°C of the observed values for no exercise input (88–96%) during the 2nd h of exercise were well above those predicted when 0.44 m/s was input to the model (44–59%), demonstrating quite clearly that predictions were better without the exercise component. Indeed, an interesting observation was that running model simulations in the 6-CTM, but not including the heat production from exercise, led to predicted T_{core} that were higher compared with simulations run at an exercise $\dot{M}$ of ~80 W/m^2 (150 W). Obviously, the metabolic heat input to the model was lower for sedentary exposure, which should theoretically lead to a faster decline in T_{core} during cold exposure compared with an exercise $\dot{M}$ of 80 W/m^2. However, as shown in Table 2, heat loss was ~25 W/m^2 less when no exercise was input into the model and potentially contributes to the higher predicted T_{core} for a "sedentary" exposure (no exercise $\dot{M}$ input into the model). However, by adding an exercise component to the 6-CTM, originally designed for sedentary exposure and exercise in warm/hot conditions, heat loss was higher during exercise, compared with rest, and did not compensate for the additional heat gained through exercise metabolism. The higher predicted HFs agree with data from Lee et al. (14) and McArdle et al. (15), who found that exercise increased HF by 70–100 W/m^2 compared with sedentary exposure at the same water temperature (15–20°C).

The predicted T_{core} for exercise inputs of 0 and 80 W/m^2 are qualitatively similar to earlier studies (11, 13) that observed lower T_{core} during whole body exercise in cold water compared with sedentary exposure in water of the same temperature. The higher metabolic rates during exercise were offset, presumably due to elevated convective and conductive heat loss caused by perfusing active muscle areas (3, 27). However, other studies (9, 14, 17, 28) report that exercise with the legs only resulted in higher T_{re} during cold-water immersion at water temperatures as low as 15°C, compared with resting conditions. These other data (9, 14, 17, 28) directly contradict the finding in the present study that predicted T_{core} values during simulated rest were higher than during simulated exercise.

Future model development. In summary, this study demonstrated that both thermoregulatory models designed for sedentary cold exposure could not be extended for use during exercise with partial immersion. The 6-CTM did successfully predict T_{core} responses in 75% of the 10°C water trials using RMSD criterion, but the 6-CTM became less valid as exposure duration increased and may be caused by an overprediction of heat loss. The 3-CTM predicted observed values in 0% of the trials and also did not predict well during the 2nd h of cold exposure. Further refinement of the 6-CTM model is needed before developing guidance for different exercise and immersion scenarios. One change that is required is a better algorithm to predict heat loss during exercise. The data from this study demonstrated that peripheral heat loss is less than the predicted 6-CTM value during exercise, suggesting the model algorithms place a greater emphasis on increased blood flow to exercising muscle, thus reducing the thermal gradient between muscle and the environment, and predicting a concomitant increase in conductive heat loss. However, there are no physiological data to confirm that the gradient across muscle, fat, skin, and water is different during exercise compared with rest. The redistribution of heat to the periphery during exercise in cold water needs to be quantified. Another modification potentially needed is developing an algorithm to predict $\dot{M}$ during combined exercise and cold water immersion. Current models treat exercise and shivering metabolism in an additive fashion, but data do suggest that exercise suppresses shivering heat production (12). A systematic examination of the relationship be-

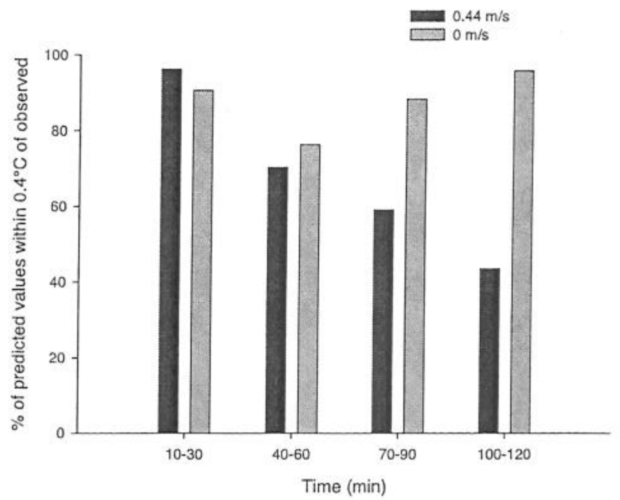

Fig. 6. Percentage of predicted values within ±0.4°C of the observed value determined using nonparametric Bland-Altman analysis for 0.44 m/s trials. 0.44 m/s refers to predicted values that included the metabolic heat production from exercise, whereas the 0 m/s refers to predicted values that assumed no metabolic heat production from exercise. Data were collapsed for all four trials and binned into four equal 20-min time intervals.

Table 2. *Actual and derived heat flows from the 6-CTM model at minute 60 of cold exposure*

	10C1	10C2	10W1	10W2	15C1	15C2	15W1	15W2
Actual	178.6 (31.1)	239.5 (20.3)	152.2 (14.8)	189.4 (26.1)	153.6 (25.5)	186.6 (19.3)	132.8 (12.0)	161.2 (28.4)
6-CTM	246.3 (11.8)	281.1 (11.6)	203.4 (7.1)	241.2 (6.9)	202.9 (7.1)	237.7 (9.5)	167.4 (6.4)	199.6 (6.9)
6-CTM (no exercise)	218.5 (10.5)		176.6 (5.8)		179.5 (6.2)		144.3 (6.2)	
n	4	6	5	8	8	8	8	9

Values are means (SD) in W/m^2; *n*, no. of subjects for each trial at *minute 60*. 6-CTM (no exercise) denotes model inputs that assumed no metabolic heat production from exercise.

tween exercise intensity, cold-water immersion, and declines in T_{core} is needed for algorithm development.

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DISCLAIMER

This study is approved for public release; distribution is unlimited. The opinions or assertions contained herein are the private views of the author(s) and are not to be construed as official or reflecting the views of the Army or the Department of Defense. The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25, and the research was conducted in adherence with the provisions of 32 CFR Part 219. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRMC Regulation 70-25 on the use of volunteers in research. Any citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement of approval of the products or services of these organizations.

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